Universität Hamburg
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Measurement of the Jet Mass Distribution in Boosted Top Quark Decays in CMS

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on behalf of the CMS Collaboration

QCD@LHC 2019 conference
(Buffalo, USA)

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Introduction: top mass measurement

Top mass is a crucial parameter for internal consistency of the Standard Model

-> How to measure it?

RESOLVED TOPOLOGY:

- Ideogram method
- Template method
- Matrix element method

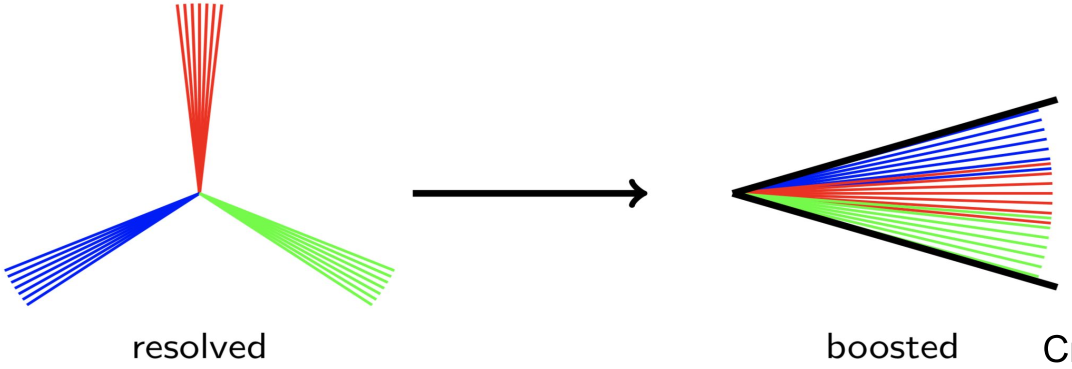
PRO: extremely precise measurement
CON: difficult to relate it to top-quark pole mass

BOOSTED TOPOLOGY:

- Mass of the jet containing top decay products

PRO: independent on top threshold effects and on top-quark mass definition

CON: larger uncertainty than resolved topology



Credits: Dennis Schwarz

Introduction: top jet measurement

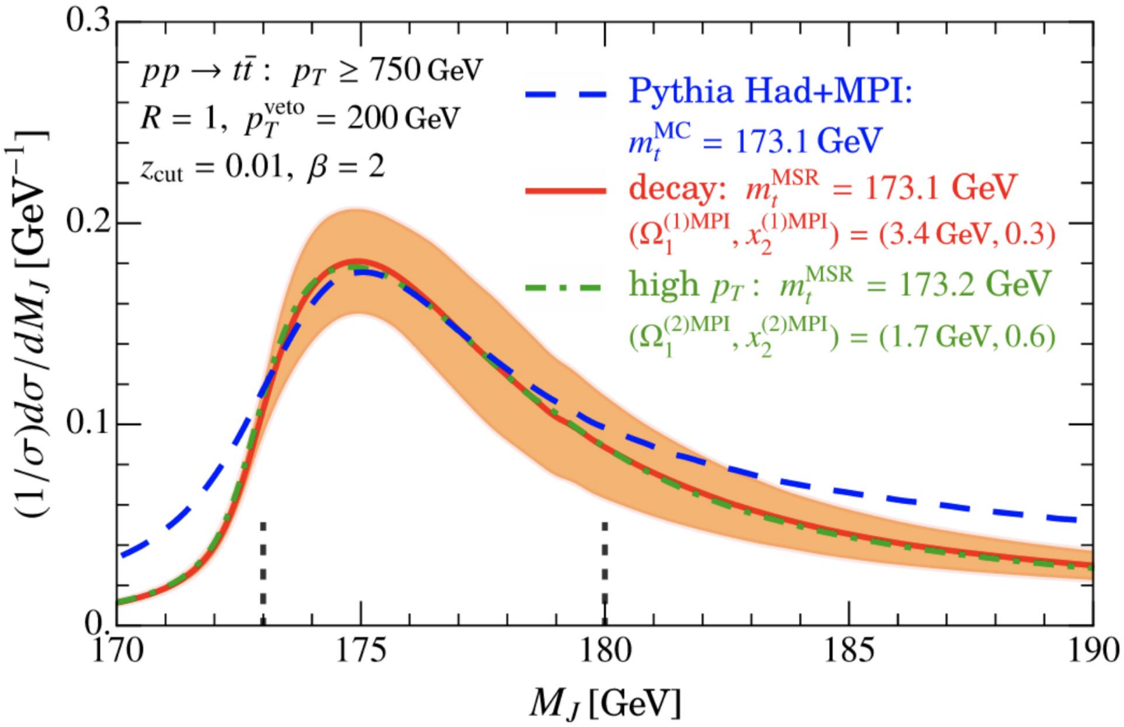
Top-jet mass is sensitive to top-quark mass

Top jet mass is an analytically calculable quantity

No ambiguity due to top mass definition

Contributions from perturbative and non-perturbative QCD

Unfolded measurements crucial for testing available theoretical predictions

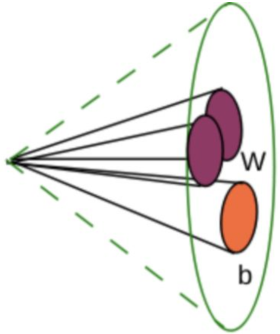


arXiv:1708.02586

Introduction: reconstruction strategy

Reconstruction of a “fat jet”, clustering all decay products of the top

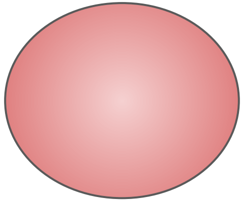
- Anti-k_T algorithm (R = 0.8)
- Cambridge-Aachen algorithm (R = 1.2)
- XCone (novel approach of 13 TeV analysis)



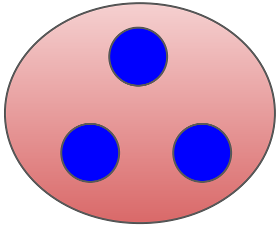
$$R \sim 2m^{top} / p_T$$

With a transverse momentum of 400 GeV, top quarks are well included in a jet of R = 1.0-1.2

- Study of the jet substructure to discriminate top jets from QCD background
- Selection of top-pair semileptonic events



QCD jets: uniform distribution of particles inside the jets



Top jets: presence of three subjets, one for each decay product

Mass of jet can be measured, e.g., from four-momenta of the subjets or all clustered particles (+soft drop..)

Boosted top jet mass measurement at 8 TeV

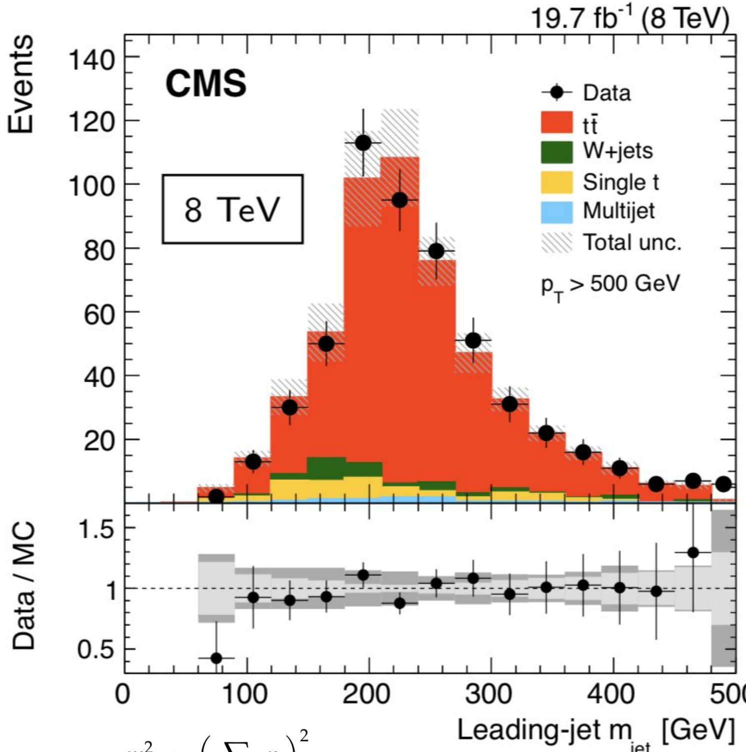
Measurement performed in lepton+jet events

- Top-jet candidate:
  - 1 jet with p_T > 400 GeV clustered with the Cambridge-Aachen algorithm (R = 1.2)

- Presence of exactly one muon (electron) with p_T > 35 (45) GeV

Unfolded absolute and normalized cross sections as a function of the top-jet candidate mass

-> Top-jet mass extraction through templates from simulation



$$m^2_{\mathrm{jet}} = \left(\sum_{i \text{ in jet}} p_i \right)^2$$

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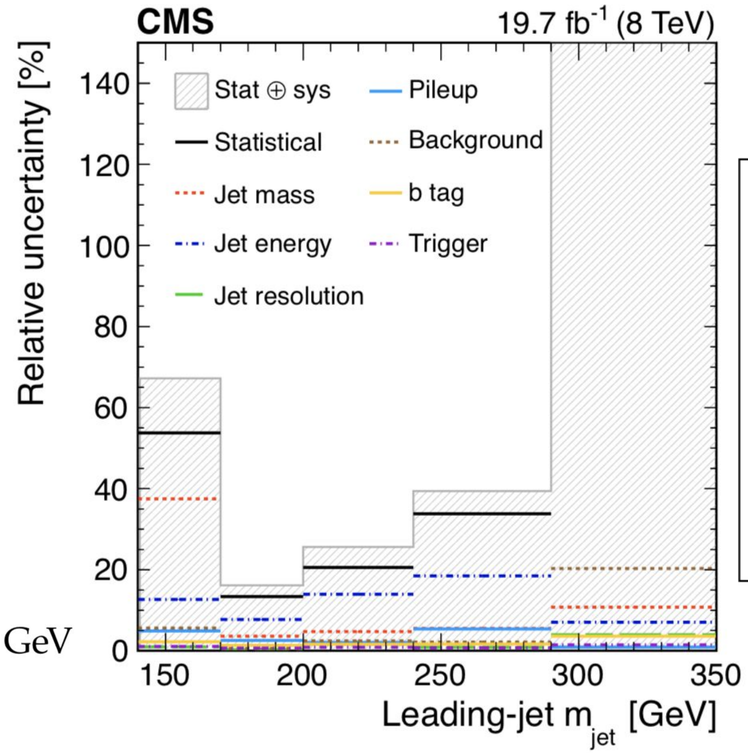
Boosted top jet mass measurement at 8 TeV

Dominant uncertainties:

- Statistical (15% in top-mass peak)
- Jet mass scale (5-10%)
- Jet energy scale (10-15%)



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Top mass value extracted from jet mass distribution:

$$
\begin{aligned}
m_t &= 170.8 \pm 6.0\,(\text{stat}) \pm 2.8\,(\text{syst}) \pm 4.6\,(\text{model}) \pm 4.0\,(\text{theo})\,\text{GeV} \\
&= 170.8 \pm 9.0\,\text{GeV},
\end{aligned}
$$

Boosted top jet mass measurement at 8 TeV

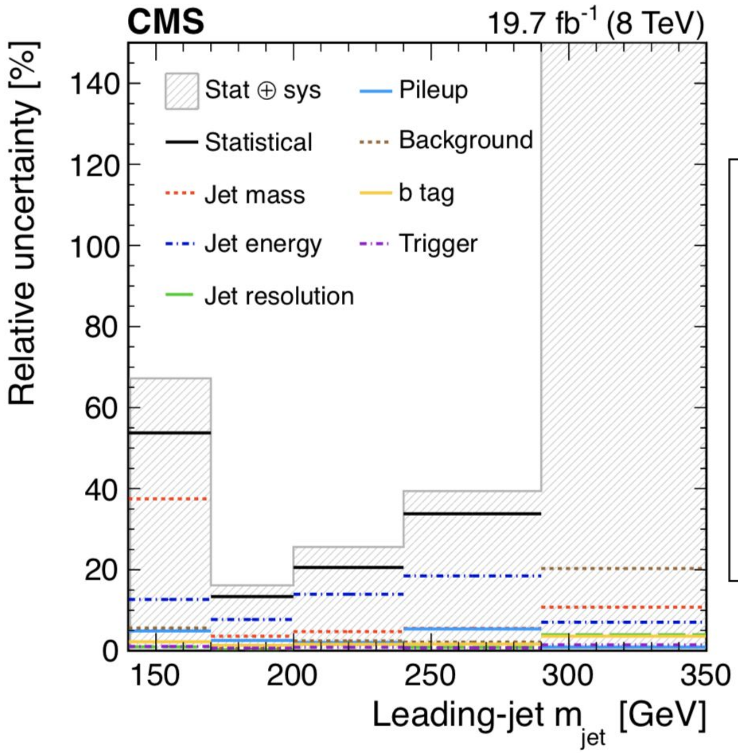
IMPROVEMENTS ACHIEVABLE AT 13 TeV:

- More data!
  - Increase in integrated luminosity
  - $\sigma^{13\ \mathrm{TeV}}$(top-pair) > $\sigma^{8\ \mathrm{TeV}}$(top-pair)

-> Decrease in statistical uncertainties

- Reduced sensitivity for pile-up and UE
  - Possibility to use smaller jets and/or different clustering algorithms

-> Decrease in pile-up and model dependence (jet mass) uncertainty



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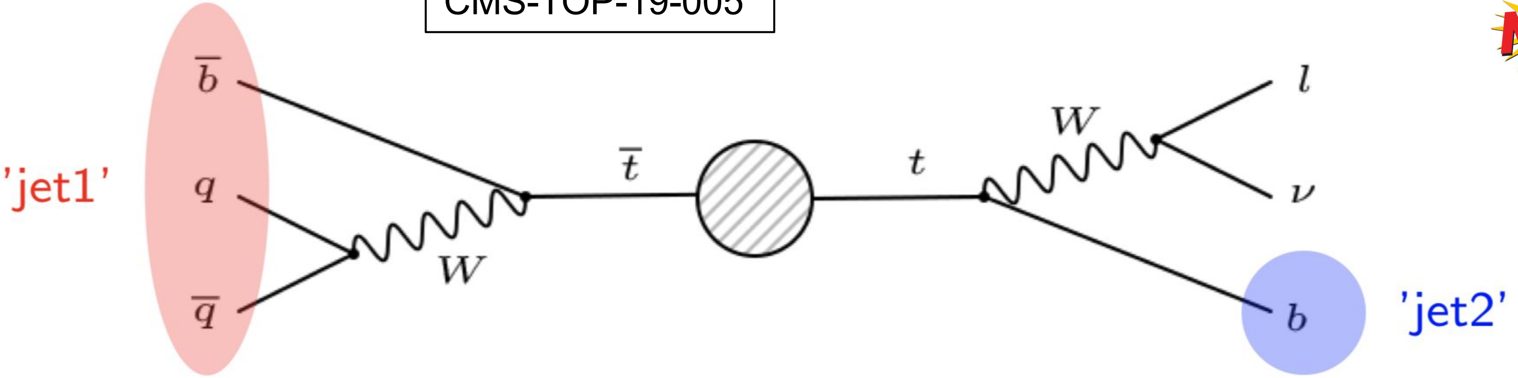
Boosted top mass measurement at 13 TeV

CMS-TOP-19-005



Credits: Dennis Schwarz

<u>Single lepton trigger</u>

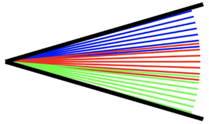
Selection of exactly one lepton with p_T > 55 GeV in $|\eta|$ < 2.4

Two XCone jets, where the top-jet (jet1) candidate needs to have 3 anti-kT (R = 0.4) subjets with pT > 30 GeV in $|\eta|$ < 2.4 (one b-tagged)

$M^{jet1} > M^{jet2+lepton}$ -> suppression of unmerged hadronic top jets

p_T^{miss} > 50 GeV

Top mass measurement performed by measuring the mass of the hadronic top jet

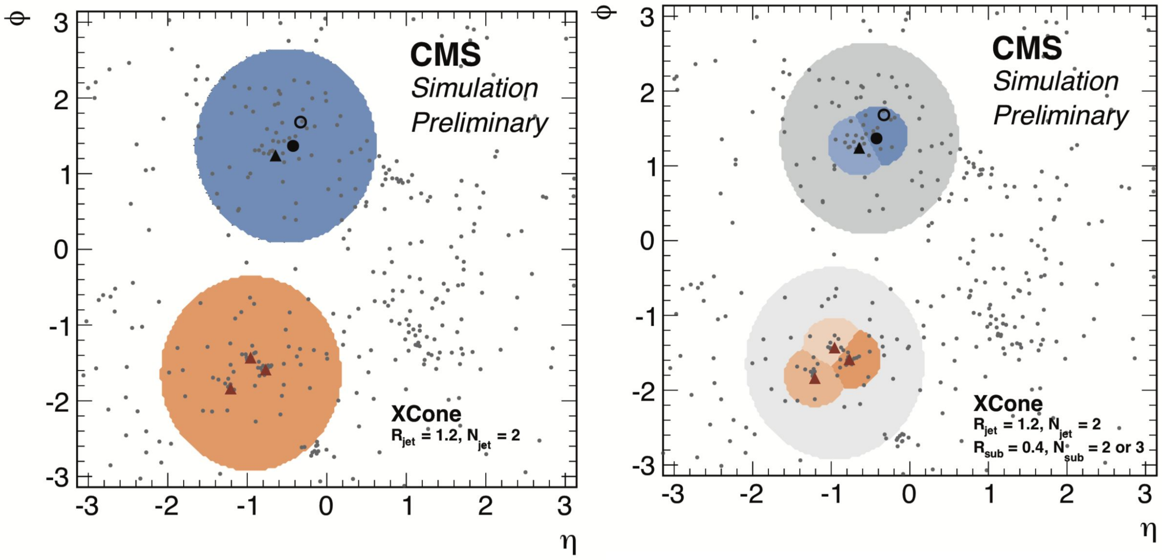


X cone jet clustering algorithm

Exclusive jet algorithm:

- It returns exactly *N* jets as output
- Jet axes found by minimizing the N-jettiness of the event
- Particles are clustered around these axes

Ref: JHEP11(2015)072

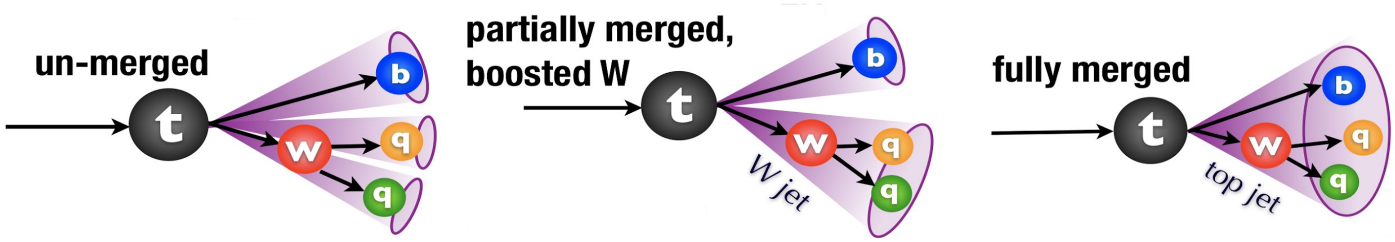


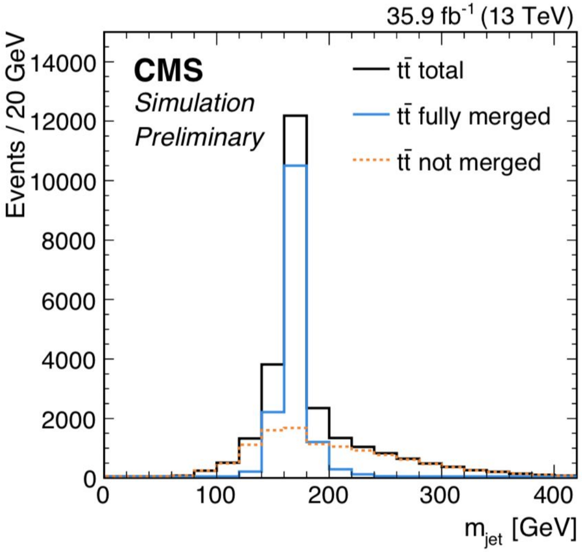
Application to semileptonic top events:

- Set N = 2 and R = 1.2
- Calculate ΔR (lep,jet) for both jets
  - Lowest ΔR (lep,jet): leptonic jet
  - Highest ΔR (lep,jet): hadronic jet
- Find subjets: 3 in hadronic jet and 2 in leptonic jet
- Combine subjets in final jets

Figure: Hadronic jet: p_T = 688 GeV, m_{jet} = 191 GeV

X cone jet clustering algorithm



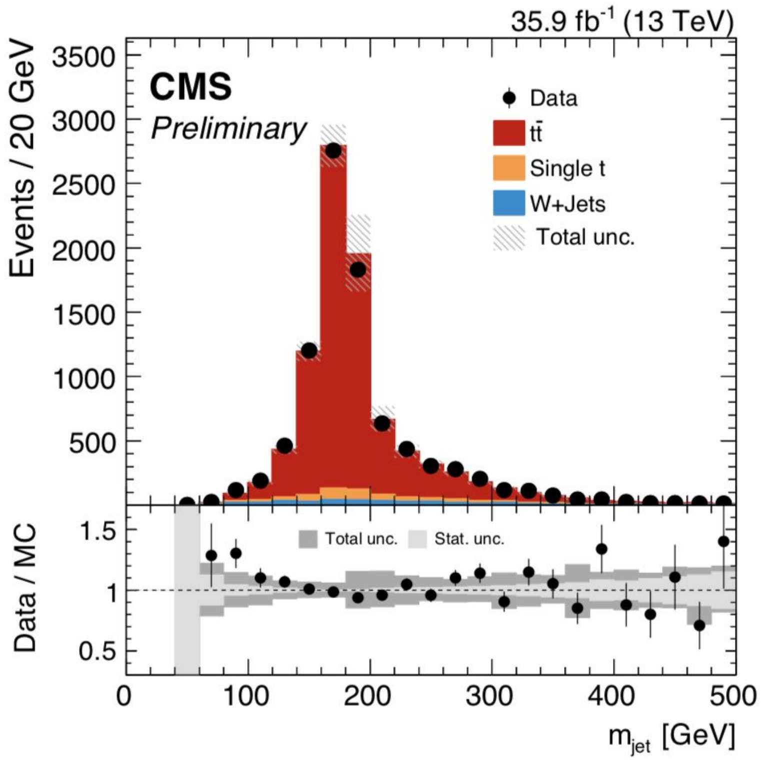


Not merged: top decay products are not associated to one of the three subjets reconstructed in the clustered jet

Fully merged: top decay products are clustered inside the fat jet and are associated to one of the three subjets

Use of XCone algorithm maximises the number of selected events and the fully-merged fraction of selected events

Boosted top mass measurement



<u>Very clean selection!</u>

Top-jet candidate mass for jets with pT > 400 GeV in $|\eta|$ < 2.4

<u>Clear peak observed at the top quark mass in data</u>

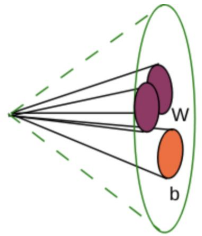
Backgrounds from W+jets and single top events (< 3%)

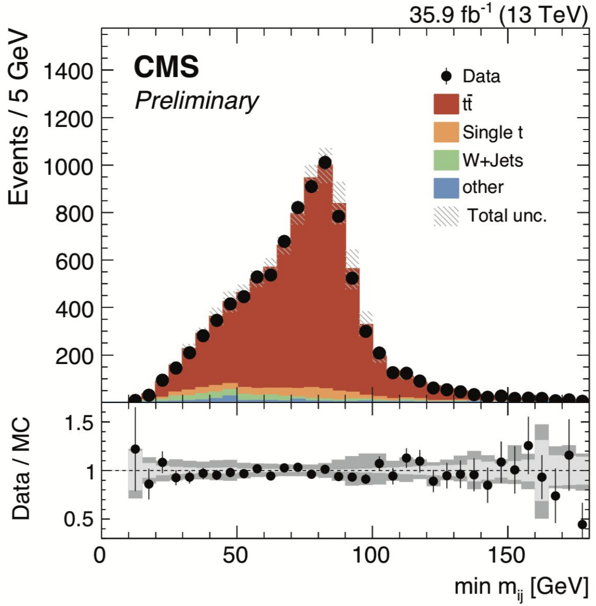
<u>Predictions from Monte Carlo generators at NLO:</u>
POWHEG+PYTHIA8 for top-antitop events,
POWHEG+PYTHIA8 for single-top events
MADGRAPH_aMC@NLO+PYTHIA8 for W+jets events

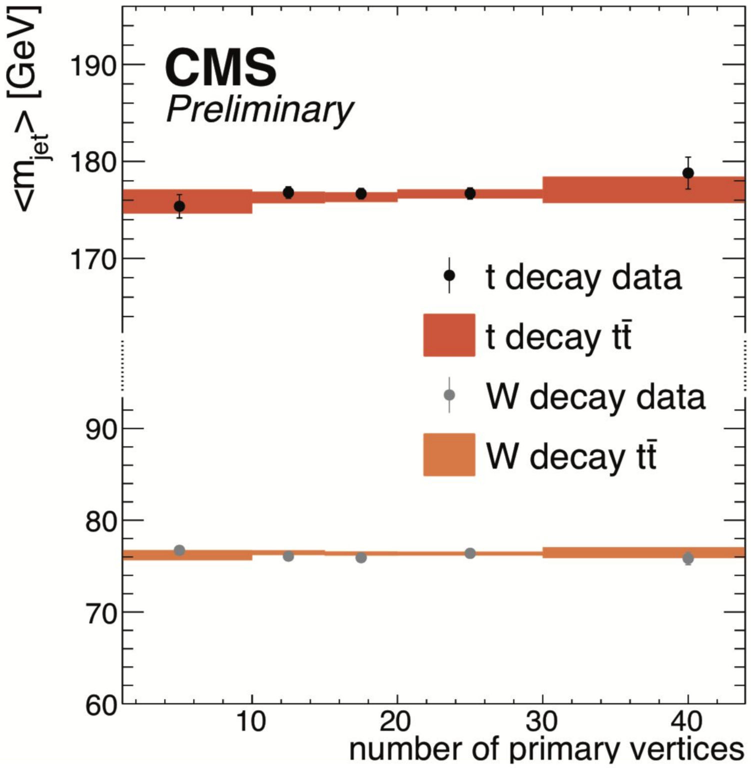
Jet mass: pile-up dependence

Jet mass response extremely stable as a function of number of reconstructed primary vertices

-> Top jet mass: mass of the 3 reconstr. subjets
-> W-jet mass: minimum mass of two subjets in the hadr. top







Unfolding procedure

Selection of semileptonic top-pair events
- Exactly one lepton with p_T > 60 GeV

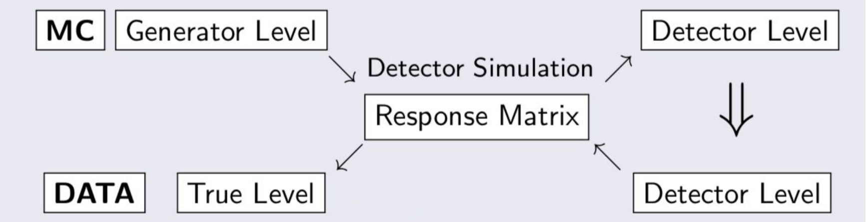
Hadronic Top-jet candidate (jet1):
- Jet with p_T > 400 GeV and three subsets with p_T > 30 GeV

$M^{jet1} > M^{jet2} + M^{lepton}$ -> suppression of unmerged hadronic top jets

PARTICLE LEVEL DEFINITION:

Unfolding takes care of the migration effects from detector to particle level

Tikhonov regularization used for unfolding results, as implemented in TUnfold package

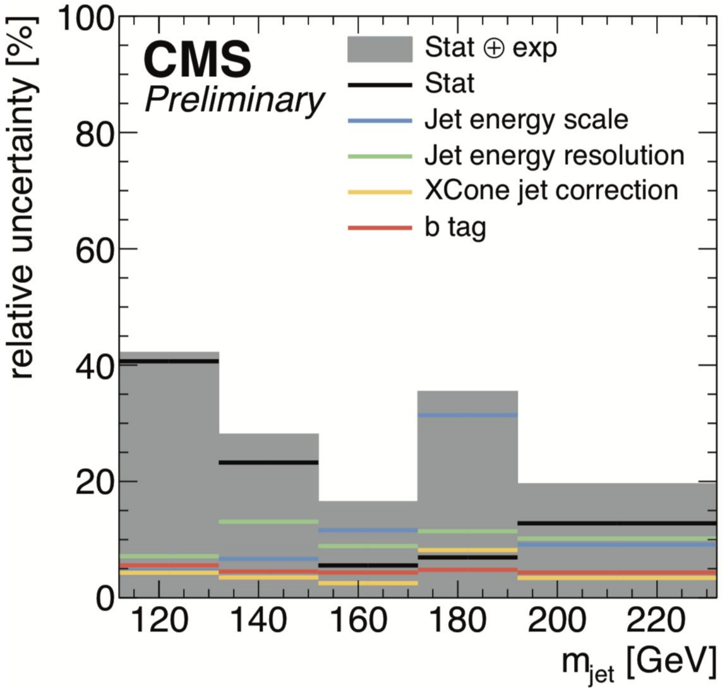


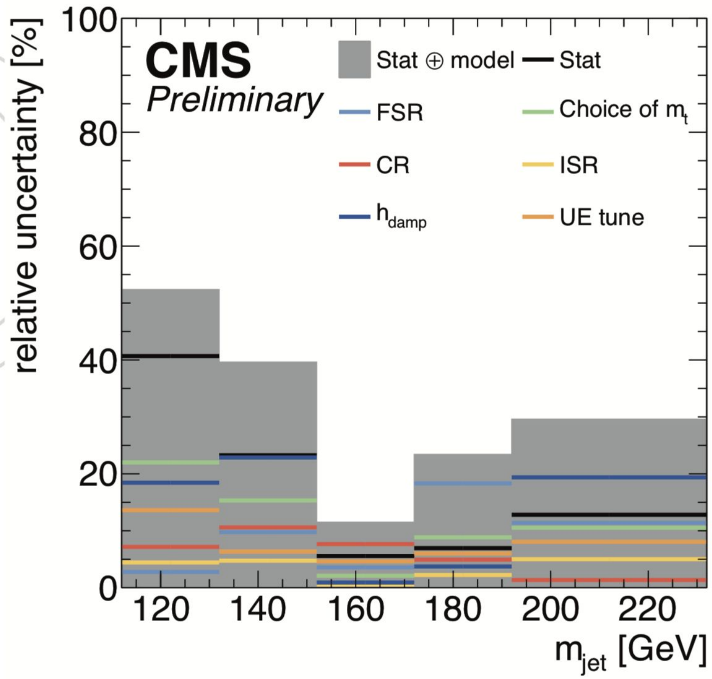
Jet mass bin widths optimized according to detector resolution and migration effects

Boosted top mass: systematic uncertainties

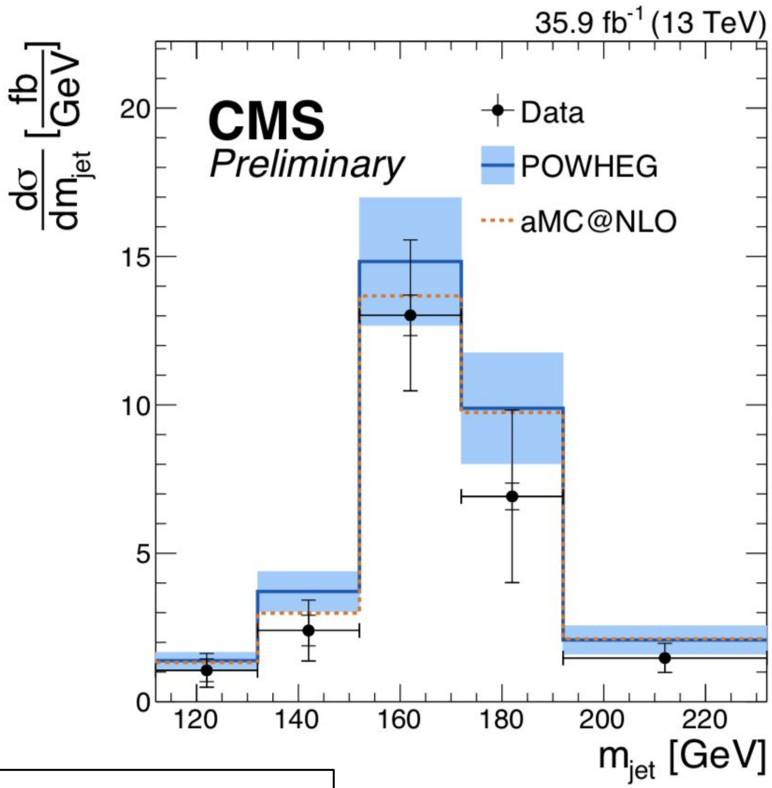
Experimental and theoretical uncertainties affecting the absolute top-jet mass cross section

- Statistical uncertainty dominates out the peak of the distribution
- Jet energy scale is the major contribution at masses around the top mass





Boosted top mass: absolute cross section



CMS-TOP-19-005

NLO predictions are able to describe very well the cross sections as a function of the top-jet mass

Unfolded distributions can be compared to analytical predictions as well

Visible cross section at particle level:

$$\begin{aligned} \sigma &= 526.8 \pm 16.7(\text{stat}) \pm 38.1(\text{exp}) \pm 28.7(\text{model,unfold})\ \text{fb} \\ &= 526.8 \pm 50.5(\text{tot})\ \text{fb}. \end{aligned}$$

NEW!

Boosted top mass: normalized cross section

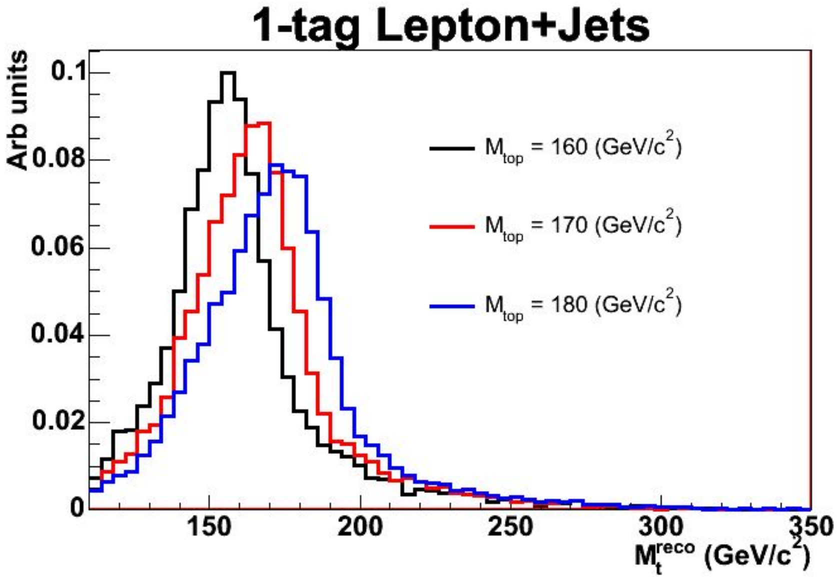
Differential cross sections are normalized to the visible measured cross section

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{jet}}$$

Used for top mass extraction through a template method

Jet mass distribution is sensitive to the choice of top-quark mass used in simulation

From CDF, for illustrative purposes



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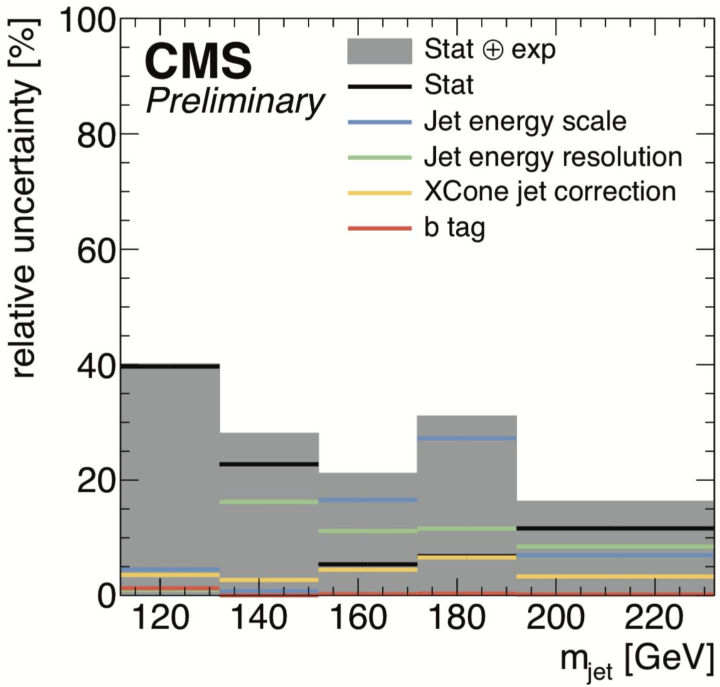
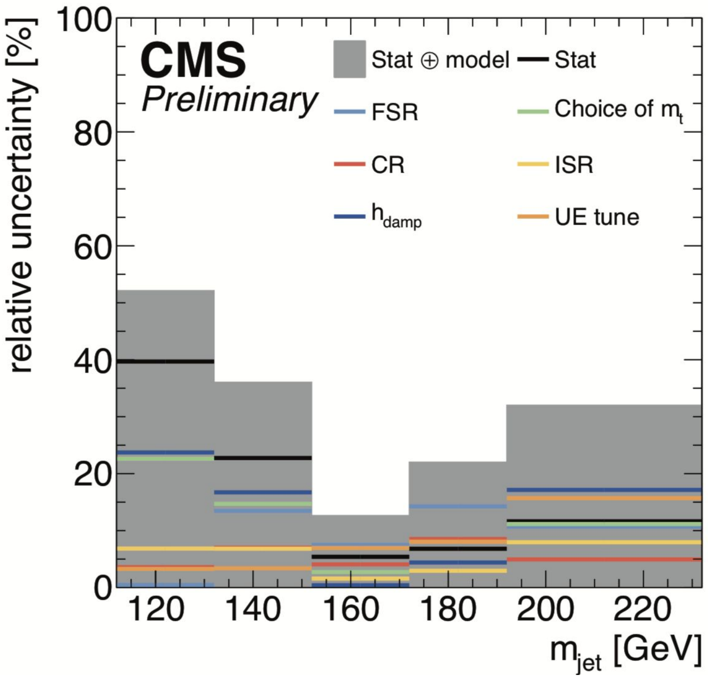
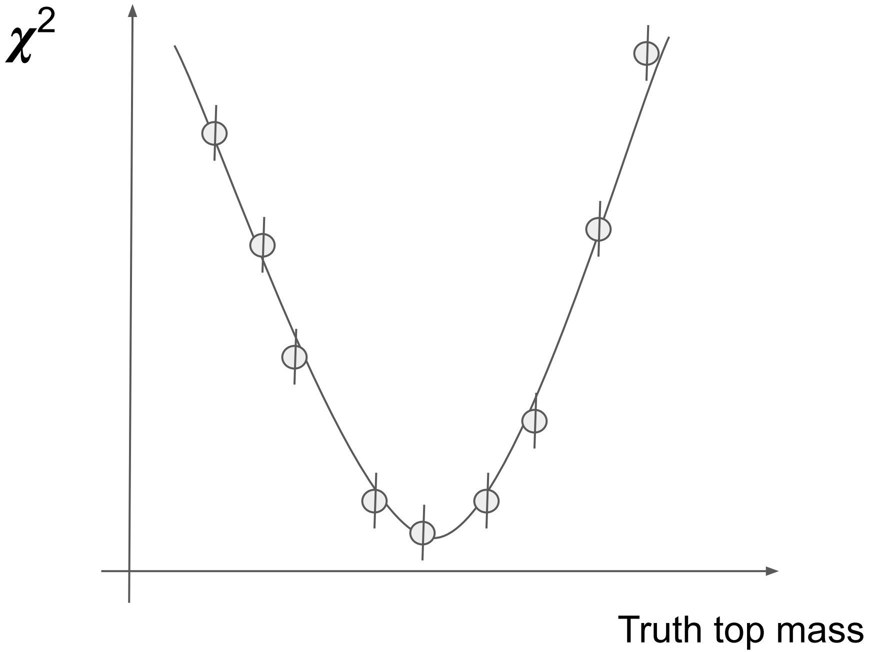




Top jet mass extraction

(Just for illustrative purposes)



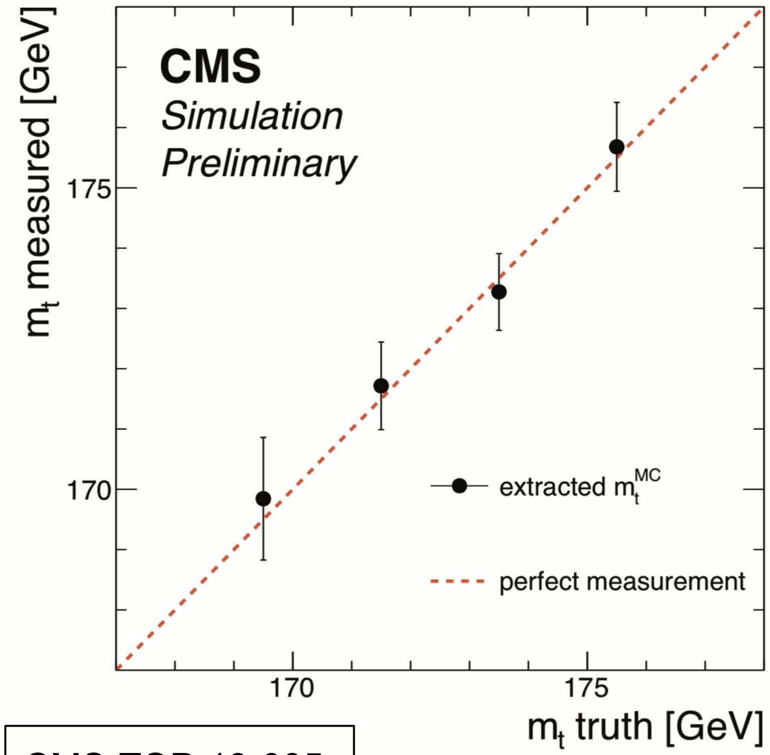
From differential cross section as a function of jet mass normalized to the visible cross section

Extraction through χ^2 minimization

- Pseudo-data from MC simulation
  POWHEG + PYTHIA 8
- Mass templates extracted from various Monte Carlo event generator predictions
  POWHEG + HERWIG++,
  MADGRAPH_aMC@NLO+ PYTHIA8

Parabolic interpolation of the χ^2 values obtained for each discrete top mass point

Top jet mass extraction



CMS-TOP-19-005

Extraction through χ^2 minimization

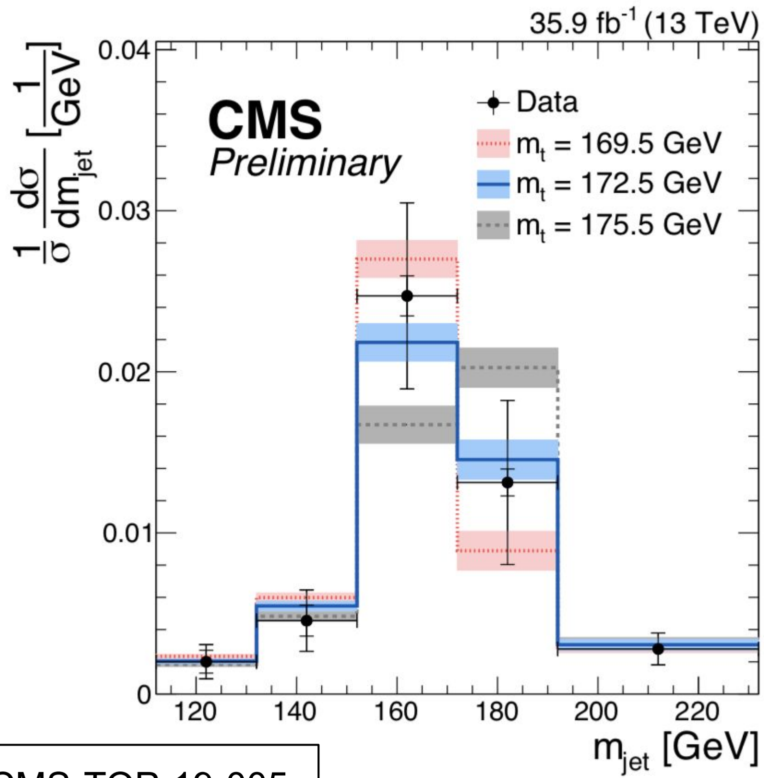
- Pseudo-data from MC simulation
  POWHEG + PYTHIA 8

- Mass templates extracted from various Monte Carlo event generator predictions
  POWHEG + HERWIG++,
  MADGRAPH_aMC@NLO+ PYTHIA8

-> No bias seen on pseudo-data tests

Measured extracted mass follows the value of the input truth mass

Top jet mass extraction



CMS-TOP-19-005

Predictions using a different input top mass exhibit a different position of the jet mass peak

NEW!

$$m_t = 172.56 \pm 0.44(\text{stat}) \pm 1.57(\text{exp}) \pm 1.55(\text{model,unfold}) \pm 1.02(\text{theo})\ \text{GeV}$$

$$m_t = 172.56 \pm 2.47(\text{total})\ \text{GeV}$$

-> factor of 4 improvement with respect to CMS measurement at 8 TeV

-> compatibility with top mass value obtained in the resolved regime

Summary and conclusions

Top mass is one of the fundamental parameters of the Standard Model

- Measurement from boosted top jets is independent on mass definition
- Jet masses are analytically calculable and could be compared to unfolded data

CMS has measured the top mass by using boosted hadronic top jets

Novel reconstruction approach using the XCone jet clustering algorithm

- Improvement in the selection of fully-merged top jets
- Improvement in jet mass resolution

Unfolded differential absolute cross section measurement as a function of jet mass will be released

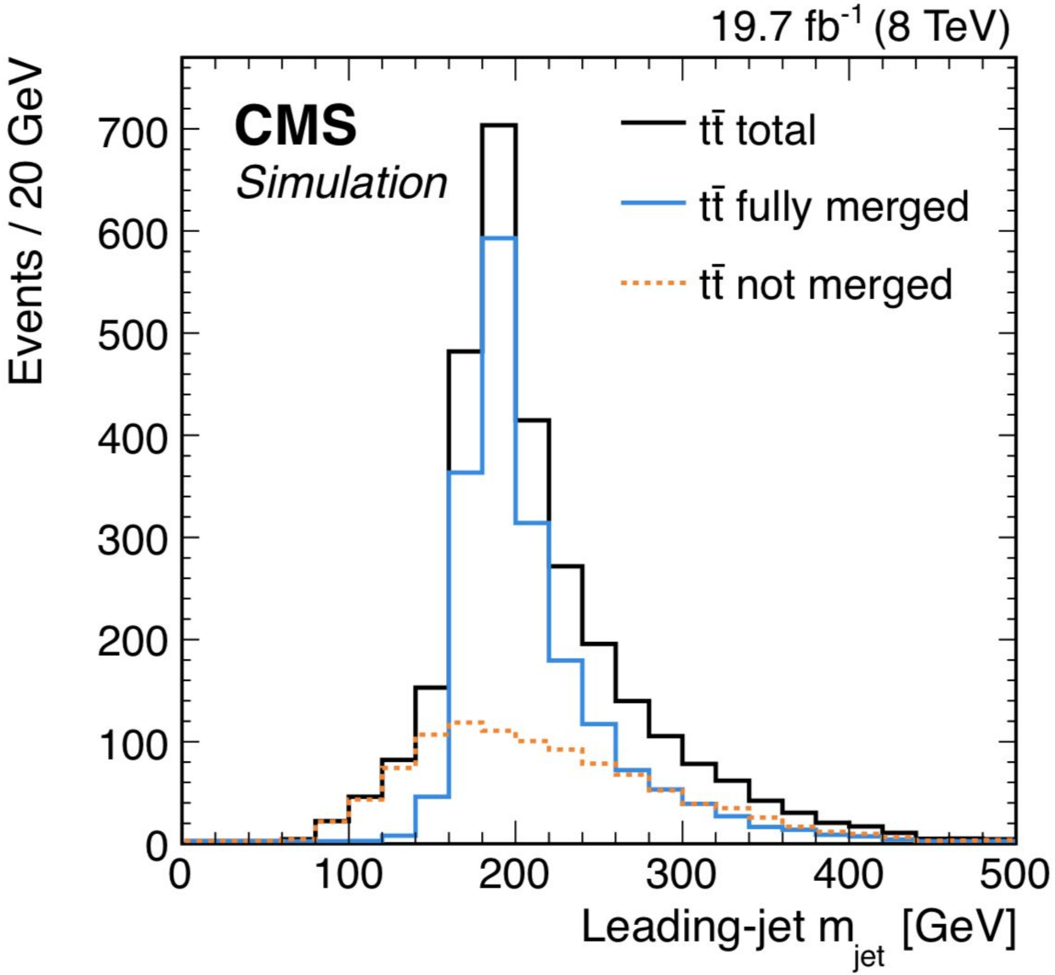
- Crucial for comparisons to various theoretical predictions

Top mass extraction performed through normalized cross sections as a function of jet mass

- Improvement of a factor of 4 with respect to CMS measurement at 8 TeV

Obtained result is compatible with measurement in resolved topologies

$m_t = 172.56 \pm 2.47(\text{total})\ \text{GeV}$ vs $M_t = 172.44 \pm 0.13\,(\text{stat}) \pm 0.47\,(\text{syst})\ \text{GeV}$



Source	Number of events
Multijet	21 ± 21
W+jets	60 ± 13
Single top quark	90 ± 21
Total background	171 ± 32
$t\bar{t}$ signal	1410 ± 152
Data	1434

Range in m_{jet} [GeV]	112–132	132–152	152–172	172–192	192–232
Integrated cross section [fb]	21	48	260	138	59
Statistical uncertainty [%]	40.7	23.2	5.6	6.9	12.8
Experimental uncertainty [%]	11.3	15.9	15.6	34.8	14.9
Jet energy scale	4.7	6.7	11.6	31.4	9.1
Jet energy resolution	7.2	13.1	8.9	11.4	10.2
XCone jet correction	4.3	3.5	2.5	8.2	3.4
b tag	5.6	4.5	4.3	4.8	4.3
Pileup	1.1	1.2	< 1	< 1	< 1
MuID	1.1	< 1	< 1	1.1	< 1
MuTrigger	< 1	< 1	< 1	1.0	< 1
ElID	< 1	< 1	< 1	< 1	< 1
ElTrigger	< 1	< 1	< 1	< 1	< 1
ElReco	< 1	< 1	< 1	< 1	< 1
Model uncertainty [%]	33.0	32.1	10.1	22.4	26.7
FSR	2.8	9.8	3.6	18.3	11.4
Choice of m_t	22.0	15.3	2.1	8.8	10.5
CR	7.2	10.6	7.7	4.9	1.3
UE tune	13.6	6.3	4.6	6.0	8.1
h_{damp}	18.4	22.9	< 1	3.7	19.4
ISR	4.4	4.7	< 1	2.2	5.0
Scale	1.1	1.7	1.7	2.7	2.2
PDF	< 1	< 1	< 1	< 1	< 1
Total Uncertainty [%]	53.8	42.8	19.5	42.0	33.3